

## 9 Aurigae: strong evidence for non-radial pulsations

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### ABSTRACT

We present further photometric observations of the unusual F0 V star 9 Aurigae and present evidence that this star's radial velocity, spectroscopic line widths and line depths are also variable with the same frequencies as the photometric data ( $f_1 \approx 0.795$  and  $f_2 \approx 0.345$  d<sup>-1</sup>). The phases of these sinusoids are stable over time scales of longer than one year, though the amplitudes can vary, making the prediction of photometric behavior impossible. Given that a variety of other explanations have already been discounted (e.g. interactions with a close companion, the existence of a lumpy, orbiting ring of dust, or star spots) and that these variations occur on time scales an order of magnitude slower than the fundamental radial pulsation period, we have very strong evidence that 9 Aurigae exhibits non-radial  $g$ -mode pulsations. Since the power spectrum of the radial velocity data shows frequency  $f_2$  but does not clearly show  $f_1$ , the present data suggest that  $f_2$  is associated with a low degree spherical harmonic ( $\ell = 1$  or  $2$ ), while  $f_1$  is associated with a higher degree harmonic. 9 Aurigae, along with such stars as  $\gamma$  Doradus, HD 224638, HD 224945, and HD 164615, appear to constitute a new class of pulsating variables. These stars are to be found at or beyond the cool edge of the Cepheid instability strip in the HR Diagram. Prior to this, only much hotter stars have been shown to exhibit non-radial  $g$ -modes.

**Key words:** Stars: individual: 9 Aur – Stars: pulsation – Stars: variables.

### 1 INTRODUCTION

Most spectroscopically normal, single F-type dwarf stars are very constant in brightness. Recently, a number of F-type stars on, or just above, the main sequence in the Hertzsprung-Russell (HR) Diagram have been shown to be photometrically variable, up to 0.1 magnitude on time scales of several hours to tens of hours.

The first of these to be identified was the bright southern star,  $\gamma$  Doradus (Cousins & Warren 1963). It was most recently studied by Balona *et al.* (1994a) and by Balona, Krisciunas & Cousins (1994b). A number of other stars of similar spectral type and luminosity class have been independently identified to be variable in brightness. This includes HD 164615 (Abt, Bollinger & Burke 1983), four peculiar variables in the open cluster NGC 2516 (Antonello & Mantegazza 1986), HD 96008 (Lampens 1987; Matthews 1990), 9 Aurigae (Krisciunas and Guinan 1990; Krisciunas *et al.* 1993), HD 111829 (Mantegazza, Poretti & Antonello 1991; note correct HD number), and HD 224638 and HD 224945 (Mantegazza & Poretti 1991; Mantegazza, Poretti & Zerbi 1994). Because these stars have such similar spectral types and absolute magnitudes, hence temperatures and

densities, it is sensible to study their similarities under the assumption that they constitute a new group of variables.

Antonello & Mantegazza (1986) first suggested that the slowly varying F stars in NGC 2516 might be undergoing non-radial pulsations. However, they felt that such a notion would be difficult to verify because the expected radial velocity and color variations would “probably [be] beyond the present precision of measurements.” They suggested star spots and ellipsoidally shaped stars as other possibilities. Waelkens (1991) independently suggested that one of the stars mentioned above, HD 96008, was undergoing non-radial pulsations. However, Mantegazza & Poretti (1994) have recently shown that HD 96008 exhibits smooth radial velocity variations with a period equal to twice the photometric period. It is almost certain that HD 96008 is an ellipsoidal star with a close companion (likely to be an M5 dwarf star).

The reason for the suggestion that one or more of these stars is undergoing non-radial pulsations is that a star with the density of an F dwarf has a fundamental radial pulsation period of 1-3 hours, and non-radial gravity modes give rise to variability on longer time scales. If an early F dwarf has

**Figure 1.** Power spectrum of the V-band photometry of 1992 February 7/8 to February 9/10, based on data by Krisciunas, Ohkura, and Akazawa and found in IAU file 244. This and power spectra of other data referenced in the text demonstrate that the photometric variations of 9 Aurigae occur on time scales much slower than  $\delta$  Scuti stars.

a period of 18 hours ( $\gamma$  Dor), or more than one day (9 Aur), it could be variable as a result of non-radial gravity modes.

The proof for this is two-fold. First, one looks for the *absence* of certain kinds of evidence.

A zeroth order consideration is whether it can be proven that 9 Aur is *not* a  $\delta$  Scuti star. This involves looking for evidence of variations on time scales of  $\approx 0.5$  to 5 hours. Data sufficient for this test are to be found in IAU files 238 and 244 of Unpublished Observations of Variable Stars (see Breger, Jaschek & Dubois 1990). This issue was particularly addressed by Krisciunas *et al.* (1991). On one occasion Abt obtained 28 radial velocities over 2.0 hours. Guinan twice obtained more than 50 differential magnitudes in 1.5 hours; Skillman one night obtained 35 photometric points in 5.6 hours; Luedke obtained 27 points in 4.1 hours; Ohshima obtained 63 points over 5.0 hours; and Krisciunas obtained 40 points over 5.2 hours. From light curves and power spectra of such data obtained on single nights or several nights in a row there is no evidence of variations with frequencies of 5 to 44 d<sup>-1</sup>, something one would expect if 9 Aur were a  $\delta$  Scuti star. (See Fig. 1 for an example.) We note, however, that variations of low amplitude ( $< 2$  millimagnitudes) in the  $\delta$  Scuti regime of frequencies are not ruled out by the data.

If there is no evidence for the existence of a close, possibly interacting companion, one can rule out the ellipsoidal star hypothesis and the notion that there is mass transfer going on. From the light curve one can tell if the star is an eclipsing binary. If a star's radial velocity is constant to within a few km s<sup>-1</sup>, the star is not likely to be a spectroscopic binary.

One of the ideas considered by a number of authors is the existence of extensive star spot areas, which give rise to small amplitude variability as the star rotates. (This is the mechanism for the variability of BY Dra stars, which are K and M dwarfs.) But if a dwarf star has a spectral type

earlier than about F5 to F7 and shows no evidence for an active chromosphere, then it will likely not have extensive spot areas (Giampapa & Rosner 1984). On the basis of the two closely spaced periods of  $\gamma$  Dor and the assumption that they could be explained by differential rotation on a spotted star, Balona *et al.* (1994b) attempted to model that star with a star spot model. They concluded, however, that the star spot model is not very plausible. For a star with non-commensurate periods of photometric variation the star spot model does not work at all.

If a star has a single, clearly defined photometric period (here assumed to be equal to the rotational period), under the assumption that we know the radius of the star from its location in the HR Diagram, we can use the projected rotational rate ( $v \sin i$ ) to derive the inclination angle  $i$ . If it follows that the star is viewed nearly pole on ( $i$  near 0), there is essentially no “horizon” beyond which any presumed star spots could disappear. In a previous paper (Krisciunas *et al.* 1993, hereafter referred to as Paper I) we found periods of 1.277 and 2.725 days for 9 Aur from a multi-longitude photometry campaign. Given the star's size of  $1.64 R_{\odot}$  (Mantegazza *et al.* 1994) and  $v \sin i = 17.80 \text{ km s}^{-1}$  (see below), we can calculate the implied inclination angle if we know the rotational period of the star. (While Mantegazza *et al.* do not give an uncertainty for the size of the star, we shall optimistically adopt  $\pm 0.2 R_{\odot}$ .) If the rotation period is 1.277 days, the implied inclination angle is  $16 \pm 2$  degrees. If the longer photometric period is the rotational period, the inclination angle would be  $36 \pm 5$  degrees, which in fact *would* allow star spots to be a possible explanation, since some known spotted stars have inclination angles on this order. Given the reasons outlined above and the absence of chromospheric activity in our slowly varying F stars, it seems unlikely that star spots are the physical cause of their variability.

The other kind of proof is more in the realm of confirmation. If a star is undergoing low degree non-radial pulsations ( $\ell \leq 2$ ) one might measure radial velocity variations of a few km s<sup>-1</sup>. For these and especially higher degree harmonics one might observe line profile variations. Examples of the type of line profile variations one might observe (for  $\ell = 1$  to 10 *sectoral* modes) are given by Vogt & Penrod (1983). For general information on non-radial pulsations, see Cox (1980) and Unno *et al.* (1989).

Balona *et al.* (1994a) report line profile variations for  $\gamma$  Doradus, and Mantegazza *et al.* (1994) show that HD 224638 can exhibit minor changes in line profile. In the case of these two stars the line profile variations are based on 9 and 3 spectra, respectively. Neither star seems to exhibit radial velocity variations.

In Paper I we sought a variety of evidence for the cause of the variability of the bright northern star 9 Aurigae. From UKIRT, IRAS, IUE, and speckle data, it showed no evidence for a close companion or an orbiting lumpy ring of dust. (It has a companion about 5 arcsec distant, which corresponds to about 100 AU. From infrared photometry this is most likely an M2 dwarf star. 9 Aur A and B are too far apart to interact in any significant way, and the fainter star, being

**Table 1.** Summary of 9 Aur photometry contained in IAU file 285E. Given is the telescope aperture, the number of nights  $N$  on which observations were made, and the number of V-band and B-band observations with respect to BS 1561. Each of Guinan’s points for the 1993/4 season represents the mean of 6 to 10 individual differential measures.

<i>Observer</i>	<i>Season</i>	<i>Aper (cm)</i>	<i>N</i>	<i>n<sub>V</sub></i>	<i>n<sub>B</sub></i>
Guinan	1992/3	76	13	177	177
Krisciunas	1992/3	15	3	13	
Guinan	1993/4	76	59	115	115
Luedeke	1993/4	20	11	86	
Krisciunas	1993/4	15	2	21	

7 magnitudes fainter in V, is much too faint to affect the optical photometry.) \*

In our search for an explanation for 9 Aurigae’s variability one of us (RFG) obtained 22 radial velocities with the Coravel radial velocity spectrometer at Haute Provence Observatory. These were obtained on 1992 April 23 and from 1993 February 10 to March 24 on a total of 14 nights and showed a range of about  $7 \text{ km s}^{-1}$ . With an internal error per measurement of about  $0.6 \text{ km s}^{-1}$ , the variations seemed significant. Furthermore, a period of just under 3 days was indicated. What was clearly needed was a more homogeneous data set – one measurement per hour for as many hours and nights as possible. Given the type of data Coravel produces, this would also allow us to see if the radial velocities, line widths, fractional line depths, and line profiles vary in a smooth way from hour to hour and from night to night.

In this paper we report extensive data runs of photometry and radial velocities of 9 Aur. Given the absence of certain types of evidence (from Paper I) and the data presented in this paper, we believe we have very strong evidence that 9 Aur is exhibiting non-radial pulsations. Given the time scales involved, they would have to be gravity modes.

## 2 OBSERVATIONS

In Table 1 we give a summary of the V-band and B-band photometry. The individual data values can be obtained by requesting IAU file 285E of Unpublished Observations of Variable Stars.

Guinan’s data, reduced by McCook (hereafter called the Guinan and McCook data), were obtained at Mt. Hopkins, Arizona, with two 76-cm Automatic Photoelectric Telescopes (APTs). One APT is operated by the Four College Consortium (FCC), the other by Fairborn Observatory. These two telescopes have photometers with matching photomultiplier tubes and filters. The APT observations were made using a 2.5 magnitude neutral density filter to reduce the stars’ count rates to reasonable levels. Luedeke’s data were obtained in Albuquerque, New Mexico. Krisciunas’ data were obtained at the 2800-m elevation of Mauna Kea, Hawaii. As in Paper I, the photometry of 9 Aur was obtained by means of differential measures with respect to BS 1561 (= HD 31134;  $V = +5.78$ ;  $Sp = A2 \text{ V}$ ). Krisciunas

used BS 1568 as a check star, while Luedeke primarily used BS 1668 as a check star. From over 300 differential measures with respect to BS 1568 and BS 1668 obtained over several years, we find no evidence that our principal comparison star, BS 1561, is variable in any way. Hence any variations of 9 Aur vs. BS 1561 we attribute solely to 9 Aur. These comparison star vs. check star observations also tell us how accurate an individual differential measurement is. For the Guinan and McCook data it is  $\pm 10$  millimagnitudes (mmag) or better. For the Luedeke data the corresponding value is  $\pm 12$  mmag, and for the most recent Krisciunas data it is  $\pm 20$  mmag. Guinan’s 1993/4 data are averages of 6 to 10 differential measures per point, implying internal errors of 3 to 5 mmag per point.

The radial velocities were obtained by RFG with the Haute Provence Coravel (Baranne, Mayor & Poncet 1979). A scanning range of  $70 \text{ km s}^{-1}$ , centred on zero heliocentric velocity, was normally used and was wide enough to encompass most (usually all) of the width of the cross-correlation dip. The normal integration time was 5 minutes, which in most cases was long enough to give an ample signal but was needed in order to reduce ‘seeing noise’. Such noise, arising from the fluctuations in the amount of light passing the entrance slit of the Coravel spectrometer, can be objectionable in short integrations, which average too few of the 5-Hz scans; the effects are particularly noticeable in traces, such as are given by 9 Aur, exhibiting wide and shallow dips.

During one particular observing run (a long run near to opposition of 9 Aur) an intensive series of measurements was made, at rather strictly timed hourly intervals whenever weather and other circumstances permitted. On one night as many as 14 consecutive hourly observations were obtained.

## 3 ANALYSIS OF PHOTOMETRY

Since Guinan and McCook’s latest data represent a number of differential measures per point, some averaging was necessary for the Krisciunas and Luedeke data, so that the data would have more comparable weighting. Given that the minimum number of differential measures per night was 3, we averaged the Krisciunas and Luedeke data by groups of 3.

In Fig. 2 we show the power spectrum of the 1993/4 data, using the Lomb-Scargle algorithm as presented by Press & Teukolsky (1988). It is cleaner than the power spectrum of the data of early 1992 presented in Paper I, which was based on only an 11 day observing campaign. In Paper I we found principal frequencies of  $\approx 0.783$  and  $\approx 0.367 \text{ d}^{-1}$ . The 1993/4 data give  $f_1 = 0.79475$  and  $f_2 = 0.345684 \text{ d}^{-1}$ . If we combine the last three seasons of data, we get  $f_1 = 0.7948$  and  $f_2 = 0.3456$ . Because of gaps in the photometry, particularly from season to season, and noting the relative complexity of the power spectra of different combinations of data, we decided that the most accurate working frequencies were obtained from the latest season. In this paper since we are primarily interested in the photometry and radial velocities of the latest season, using the frequencies derived from the latest data seems sensible. In section 5 below we suggest slight revisions to these periods for longer term studies.

Once we decided on the working frequencies, software obtained from Luis Balona allowed us to fit the data accord-

\* Hereafter, when we say 9 Aur we mean the primary, 9 Aur A.

**Figure 2.** Power spectrum of the V-band photometry of 1993 September 3/4 to 1994 February 5/6.

**Table 2.** Amplitudes ( $A_i$ , in mmag) and phases ( $\phi_i$ ) of Fourier fit to the 1993/4 V-band data using epoch JD 2449000.0 and frequencies  $f_1 = 0.79475$  and  $f_2 = 0.345684 \text{ d}^{-1}$ . The standard deviation of an individual data point in the two frequency fit is  $\pm 12.1$  mmag.

$i$	$A_i$	$\phi_i$
1	$13.8 \pm 1.4$	$-0.114 \pm 0.016$
2	$12.2 \pm 1.4$	$-0.481 \pm 0.018$

ing to the following functional form:

$$\Delta V = A_1 \cos 2\pi(f_1 t + \phi_1) + A_2 \cos 2\pi(f_2 t + \phi_2) + \dots$$

giving the amplitudes  $A_i$  and the phases  $\phi_i$  of the sinusoids given the known frequencies  $f_i$ . In Table 2 we give the least-squares results of the 1993/4 photometry.

Fig. 3a shows the corresponding power spectrum if the sinusoid associated with frequency  $f_2$  is subtracted from the data set. Similarly, Fig. 3b shows the power spectrum if the sinusoid with frequency  $f_1$  is subtracted from the original data set. There are still one-day aliases present in the power spectra, owing to the fact that almost all the data were taken in Arizona and New Mexico, which are almost at the same longitude. But Figs. 3a and 3b indicate that 9 Aur’s photometric variations can be described well by two sinusoids.

How can we decide if  $f_1$  or  $1 - f_1$  is the true frequency? Firstly,  $f_1$  is the highest peak in Figs. 2 and 3a. That is good, but not definitive proof. In Fig. 4 we show the data from a particular 32 day period in the fall of 1993, in which we have folded the data by  $P_1 = 1.25826 \text{ d}$  after subtracting out the sinusoid characterized by  $P_2 = 1/f_2 = 2.89282 \text{ d}$ . Note the two sets of 4 points obtained on Julian Dates 2449297 and 2449312, respectively. If we had folded the data by  $1/(1 - f_1) \approx 4.87$  days, the points from these two nights would appear

**Figure 3.** (a) Power spectrum of the V-band photometry, with  $f_2$  sinusoid subtracted out. The frequency  $f_1$  and its one day alias are clearly present. (b) Power spectrum of the V-band photometry, with  $f_1$  sinusoid subtracted out. The frequency  $f_2$  and its one day alias are clearly present.

as nearly vertical “posts” in the folded light curve instead of following the general run of data from other nights.

A further piece of evidence that  $f_1$  and not  $1 - f_1$  is the true frequency comes from an analysis of the data obtained by Guinan and McCook from 1993 January 30 to February 26. We obtain  $\phi_1 = -0.143 \pm 0.011$  using the same epoch, which compares very well with  $\phi_1 = -0.114 \pm 0.016$  from Table 2. A folded plot of the early 1993 data is to be found in Krisciunas (1994) and is not reproduced here.

A similar analysis gives  $\phi_2 = -0.419 \pm 0.026$  for the early 1993 data, vs.  $\phi_2 = -0.481 \pm 0.018$  from Table 2. These differences are not significant, or indicate a value for the frequency  $f_2$  slightly different from the one adopted (see below).

This is strong evidence not only that  $f_1$  and  $f_2$  are true frequencies, but that the physical mechanism associated with the photometric variations can be stable over time scales of one year or longer. Interestingly,  $f_2$  but *not*  $f_1$  shows up in the power spectrum of radial velocities (see below).

**Figure 4.** Differential V-band photometry of 9 Aur vs. BS 1561 from Julian Dates 2449297.7 to 2449328.9, folded by  $P_1 = 1.25826$  d, after subtraction of the sinusoid with  $P_2 = 2.89282$  d. The open triangles represent data from JD 2449297, while the open circles represent data from JD 2449312.  $\Delta V$  is in the sense 9 Aur *minus* BS 1561.

**Figure 6.** Differential B-V colors for 9 Aur vs. BS 1561. The data cover the same range of dates, and symbols are the same as in Fig. 4.

**Table 3.** Amplitudes ( $A_i$ , in mmag) and phases ( $\phi_i$ ) of Fourier fit to the 1993/4 B-V colors using epoch JD 2449000.0 and frequencies  $f_1 = 0.79475$  and  $f_2 = 0.345684$  d $^{-1}$ . The standard deviation of an individual data point in the two frequency fit is  $\pm 5.3$  mmag. Note that, within the errors, the phases match those of the V-band photometry given in Table 2.

$i$	$A_i$	$\phi_i$
1	$4.9 \pm 0.7$	$-0.106 \pm 0.023$
2	$3.7 \pm 0.7$	$-0.462 \pm 0.030$

**Figure 5.** Amplitudes  $A_1$  and  $A_2$ , in mmag, vs. time. The error bars for the abscissa represent the range of dates for the subsets of the data. The error bars for the ordinate are derived from the least-squares Fourier fit. The solid dots connected by a dashed line are for  $A_1$ , while the open circles connected by a solid line are for  $A_2$ . The right-most points have been slightly offset from each other in the X-direction for display purposes.

One unresolved issue is the variations of the amplitudes of the sinusoids. We find that  $A_1$  in particular varies over quite a range (see Fig. 5), making the prediction of future variations of the star impossible, unless it can be shown how the amplitudes vary with time.

Since Guinan and McCook obtained equivalent B-band data, we can investigate the variations of color in 9 Aur. In Fig. 6 we show the folded plot of  $\Delta(B - V)$  colors from data of the same period covered in Fig. 4. Since “ $\Delta$ ” is in the sense 9 Aur *minus* BS 1561 and the least positive  $\Delta(B - V)$

corresponds to the bluest color for 9 Aur, one can clearly see that 9 Aur is bluest (i.e. hottest) when it is brightest. This is the case for both the  $f_1$  and  $f_2$  sinusoids, since the phases  $\phi_i$  derived from the  $B - V$  colors match the phases derived from the V-band photometry (compare Tables 2 and 3). We note that the mean B-V amplitudes of the 1993/4 season about about one-third of the V-band amplitudes.

#### 4 RADIAL VELOCITIES

A number of reliable values in the literature (Abt & Levy 1974; Takeda 1984; Duquennoy, Mayor & Halbwachs 1991) suggested that the radial velocity of 9 Aur was slightly variable. After Griffin demonstrated in early 1993 that the radial velocity of 9 Aur was indeed variable, a concentrated set of 83 data points was obtained from 1993 December 25 to 1994 January 9. These are shown in Fig. 7. Five more values were obtained from 1994 February 16 to 20, and seven more from April 29 to May 4. The radial velocities range from  $-5.50 \pm 0.61$  to  $+5.15 \pm 0.66$  km s $^{-1}$ . One can clearly see hour to hour and day to day variations.

In Fig. 8 we plot the power spectrum of the radial velocity data shown in Fig. 7.  $f_2$  is clearly the dominant peak in the power spectrum. Interestingly enough, while the frequency  $f_1$  and its one day alias  $1 - f_1$  are clearly present in the photometry,  $f_1$  apparently does not show up in the

**Figure 7.** Radial velocities of 9 Aur, obtained by Griffin at Haute Provence Observatory. Top—data of JD 2449347.0 to 2449353.0; middle—data of JD 2449353.0 to 2449359.0; bottom—data of JD 2449359.0 to 2449365.0. The middle and bottom panels have been vertically offset by -12 and -24 km s<sup>-1</sup>, respectively.

radial velocity data. In Fig. 8 there is a peak *near*  $1 - f_1 \approx 0.20$  d<sup>-1</sup> (namely at  $0.248$  d<sup>-1</sup>). The small peak *near*  $f_1$  is not significant. We do not understand how *only* the one day alias of  $f_1$  should appear, but not the frequency itself, if indeed the peak near  $1 - f_1$  is the one day alias of  $f_1$ .) It could be that during the time most of the radial velocities were obtained (a period of only 15 days) the frequency  $f_1$  was in abeyance. Future observations are clearly warranted.

Since high degree spherical harmonics delineate a large number of regions on the star (which are alternatingly moving in and out or transversely), while low degree harmonics delineate a small number regions (e.g. 2 to 4 for  $\ell = 1$  or 2), one would only see radial velocity variations in a star pulsating radially or in a low order harmonic. It follows that  $f_2$  must be related to a low degree harmonic.

Since  $f_1$  apparently does not show up in the radial velocity data, it seems unwise to make a two frequency fit to the radial velocity data to derive the phases and amplitudes. The peak of  $f_2 \approx 0.36 \pm 0.03$  is close to  $f_2 = 0.345684$  from the photometry. Adopting the latter value and using all 95 radial velocities available from the 1993/4 season, we find  $A_{RV} = 2.00 \pm 0.27$  km s<sup>-1</sup> and  $\phi_{RV} = -0.139 \pm 0.021$  (which is the phase of maximum *positive* radial velocity). The standard deviation of an individual point in this single sinusoid fit is  $\pm 1.81$  km s<sup>-1</sup>, about three times the typical internal error of a Coravel radial velocity of this star. Carrying out a two sinusoid fit to the data does not improve this standard deviation significantly.

**Figure 8.** Power spectrum of radial velocities shown in Fig. 7. The frequency  $f_2$  and its one day alias  $1 + f_2$  are indicated.

The next question to ask is: Are the radial velocities in phase with the photometry? In Fig. 9 we show all 95 radial velocities from the 1993/4 season folded by  $P_2$ , using the epoch of zero phase derived from the photometry of the same season. The data qualitatively suggest that 9 Aur has the most negative radial velocity (i.e. most rapid motion

**Table 4.** Observed phases  $\phi_1$  for three consecutive seasons of photometry of 9 Aur, using epoch JD 24449000.0 and assuming  $f_1 = 0.79475 \text{ d}^{-1}$ .

Season	Mean JD	$\phi_1$
1991/2	2448657.98	$-0.205 \pm 0.028$
1992/3	2449031.15	$-0.143 \pm 0.011$
1993/4	2449312.31	$-0.114 \pm 0.016$

**Figure 9.** Folded plot of radial velocity data from the 1993/4 season, using epoch of zero phase and period derived from the photometry. The sinusoid shown is derived from the Fourier fit of the radial velocities. Qualitatively, the star's maximum rate of expansion corresponds to the time of minimum light for the  $f_2$  sinusoid.

towards us) close to the time of minimum light for the  $f_2$  sinusoid. The observed phase lag is  $\Delta\phi = 0.158 \pm 0.028$  in the sense that the most negative radial velocity occurs after minimum brightness. This phase lag is statistically significant, but given the scatter of the data in Fig. 9, it is probably unwise to make much of it. Balona & Stobie (1979) and Watson (1988) discuss how the amplitudes and phases of the V-band photometry, photometric colors, and radial velocities can be used to investigate the pulsational mode(s) of a star, but given the small range of the 9 Aur data compared to the errors, we feel that detailed modelling along these lines is beyond the scope of this paper.

Another question to ask is: Do the radial velocities of the 1993/4 season phase up with the radial velocities from the previous season? This is difficult to say with the same certainty as can be said from the analysis of the photometry, since there were only 21 radial velocities obtained on 13 nights in 1993 February and March. An analysis of the early 1993 radial velocities shows that  $f_2$  is once again the biggest peak in the power spectrum, and we obtain  $\phi_2 = -0.060 \pm 0.043$  for that data set. (The data set is not substantial enough to say anything certain about the presence or absence of  $f_1$ .)

## 5 REVISION OF THE PERIODS

The data of the most recent season give us accurate working periods, which allow us to investigate if data sets from more than one year give nearly equal phases. It turns out that this is the most effective way to adjust the periods so that recent data may be compared with data obtained in the future.

From Griffin's radial velocity data of the past two seasons we find  $\Delta\phi_2 = -0.079$  over 125 cycles of 2.89282 days, or an error in the period of 0.00183 d. From the photometry we find  $\Delta\phi_2 = -0.062$  over 97 cycles, or an error in the pe-

riod of 0.00185 d. We obtain a revised period  $P_2 = 2.89282 + 0.00184 = 2.89466 \text{ d}$ , or  $f_2 = 0.345464 \text{ d}^{-1}$ .

In Table 4 we show the corresponding phases of the  $f_1$  sinusoid for the past three seasons of photometry. When plotted vs. the mean Julian Date of the observations in question they give a tight linear fit. We may correspondingly adjust the period  $P_1 = 1.25826 - 0.00022 = 1.25804 \text{ d}$ , or  $f_1 = 0.79489 \text{ d}^{-1}$ .

Subsequent photometry or radial velocities would be needed to confirm if we have really determined  $P_2$  and  $P_1$  as accurately as they are given in this paper. To do so would be significant, for it would mean that one or both of the frequencies revealed in the data are indeed very stable. Knowing the periods exactly is not important for the purposes of this paper. What is important is: 1) there are two periods (not one or 100); 2) the periods are not closely spaced (as in  $\gamma$  Dor); and 3) one period is not a simple multiple of the other ( $P_2/P_1 \approx 2.30$ ).

## 6 LINE WIDTHS AND FRACTIONAL LINE DEPTHS

Coravel works by scanning the star spectrum back and forth across a mask which is analogous to a high-contrast photographic negative of the spectrum. The data acquisition system produces a profile that represents the cross-correlation between the spectrum and the mask; it can be thought of as the mean profile of the stellar lines. The reduction procedures determine the radial velocity from each cross-correlation profile, and also give the line depth and a parameter characterizing the width. The width parameter can be interpreted in terms of the projected rotational velocity  $v \sin i$  of the star (Benz & Mayor 1981).

In the case of 9 Aur the mean projected rotational velocity is  $17.80 \text{ km s}^{-1}$  from all the Coravel data, 1992 April 23 to 1994 May 4. The formal internal error of  $v \sin i$  is  $\pm 0.33 \text{ km s}^{-1}$ , but a more realistic uncertainty is  $\pm 1.0 \text{ km s}^{-1}$ . This implies a rotational period of 4.66 days times  $\sin i$ , adopting a radius of  $1.64 R_\odot$  from Mantegazza *et al.* (1994). However, since the non-radial oscillations that we assert to be occurring on 9 Aur are broadening the line profiles, perhaps we should consider that the projected rotational velocity is no more, and may be less, than corresponds to the smallest observed values of the line width ( $\approx 15 \text{ km s}^{-1}$ ), in which case the true rotational period of the star is not less than about 5.5 days times  $\sin i$ .

In Fig. 10 we show the 95 stacked autocorrelation diagrams from the 1993/4 season. There are different numbers of line profiles per graph because we wanted to avoid splitting up data from a given night. But it is obvious that the line width and fractional line depth of 9 Aur is not con-

**Figure 10.** Coravel autocorrelation diagrams of 9 Aur data from 1993/4 season. They are labeled with the corresponding Julian Dates (minus 2440000). The line fits are given by the Coravel data reduction software. Two sets of data which had poor baseline fits on the positive velocity end have been eliminated from the analysis of this paper.

stant. This is a key signature of a star pulsating in one way or another.

For comparison we investigated the variance of the line profiles and fractional line depths of BS 3325, a star of spectral type similar to 9 Aur. The observations were made on

many of the same nights, with the instrument in the same configuration. (BS 3325 is a spectroscopic binary whose radial velocity ranges  $120 \text{ km s}^{-1}$  on a time scale of about 4.5 days. See Griffin, Eitter & Appleton (1995) for details.) In the case of BS 3325 the line widths and fractional line



**Figure 10.** Continued

depths produce classically Gaussian and much narrower histograms (a factor of 2 narrower) compared to 9 Aur. Thus, we can be assured that the observed variations of line profile, line width, and fractional line depth observed in 9 Aur are inherent in 9 Aur and are not artefacts of the Coravel instrument or data reduction procedures.

In Figs. 11 and 12 we show the power spectra of the line

widths and fractional line depths derived from the Coravel data. Compared to the power spectrum of the radial velocities shown in Fig. 9, frequency  $f_1$  is clearly present in the power spectra of line widths and fractional line depths. Since line profile variations are much more pronounced in higher degree spherical harmonics ( $\ell \geq 3$  – see Vogt & Penrod 1983), at face value the evidence presented here points

**Figure 11.** Power spectrum of the line widths of 9 Aur from the Coravel data of the 1993/4 season.

**Figure 12.** Power spectrum of the fractional line depths of 9 Aur from the Coravel data of the 1993/4 season. The frequency labeled X could be equal to  $1 - f_2$  (a one day alias).

to the following conclusion: in 9 Aur  $f_2$  comes from a low degree harmonic ( $\ell = 1$  or  $2$ ) while  $f_1$  comes from a higher degree harmonic.

## 7 DISCUSSION

From extensive photometry in 1993 and early 1994 we have confirmed that there are two primary frequencies present in the light curve of 9 Aur. Our best estimate of one frequency is  $f_1 = 0.79489 \text{ d}^{-1}$ , or  $P_1 = 1.25804 \text{ d}$ , with an epoch of zero phase (when the star is faintest) of JD 2449000.20  $\pm$  0.02. Our best estimate for the other frequency is  $f_2 = 0.345464 \text{ d}^{-1}$ , or  $P_2 = 2.89466 \text{ d}$ , with an epoch of zero phase of JD 2449001.19  $\pm$  0.05. Because the amplitudes of these sinusoids can change, it is not possible to forecast a light

curve. Future observations might reveal if there is a pattern to the variations of the amplitudes.

We note that our frequency  $f_1$  is essentially equal to a principal frequency of  $0.80 \text{ d}^{-1}$  in the light curves of HD 224638 and HD 224945 (Mantegazza *et al.* 1994). The two frequencies of  $\gamma$  Dor are  $f = 1.32098$  and  $f = 1.36354 \text{ d}^{-1}$  (Balona *et al.* 1994b). For HD 164615 the principal frequency is  $f \approx 1.227 \text{ d}^{-1}$  (Abt *et al.* 1983).

The radial velocity of 9 Aur is indeed variable, with an amplitude (semi-range) of  $2.0 \text{ km s}^{-1}$ . A power spectrum of the radial velocity data of 1993/4 clearly shows  $f_2$ , but the data do not clearly reveal  $f_1$ . Should the power spectrum of the radial velocities of 9 Aur continue to show only  $f_2$  and not  $f_1$ , it would imply that  $f_2$  is related to a low degree spherical harmonic ( $\ell = 1$  or  $2$ ), while  $f_1$  is related to a higher degree harmonic.

We have found that the  $B - V$  color of 9 Aur is bluest when the star is brightest, for both the  $f_1$  and  $f_2$  sinusoids. For Cepheids, which pulsate radially, this is also true. In Cepheids one observes the maximum negative radial velocity (i.e. the star is expanding) at the time of maximum brightness (Joy 1937). For 9 Aur the maximum negative radial velocity coincides approximately with the *minimum* brightness of the star, but we can only say this as it pertains to the frequency  $f_2$  because frequency  $f_1$  was not obviously present in the radial velocity data.

From the absence of certain evidence (i.e. the existence a close, interacting companion, a lumpy orbiting ring of dust, or plausible star spot models) and the demonstration that the radial velocities, line profiles, line widths, and fractional line depths of 9 Aur are variable with the very same frequencies found in the photometry, we believe that 9 Aur is exhibiting non-radial pulsations. They must be non-radial gravity modes because the periods of variation are at least an order or magnitude slower than the fundamental radial pulsation period.

Eddington once said that observations should not be believed unless they are supported by a good theory (Haramundanis 1984). This highlights one of the problems of this research topic. So far no successful pulsation mechanisms have been discovered which result in realistic models of F dwarf stars exhibiting non-radial gravity modes (A. Gautschi, private communication). Applying canonical thermal time scale arguments in connection with the working of a  $\kappa$ -mechanism, one would expect a large number of modes to be excited simultaneously. (The involved thermal time scale is of the order of a day and the period spacing around an oscillation period of one day is  $3 \times 10^{-3}$  days.) The observed situation calls for a sharp resonance condition that destabilizes particular modes only. Since it seems quite certain that we have serendipitously discovered a new class of variable stars, it is important to produce better models of early F stars so that we can understand under what conditions these stars show evidence for non-radial pulsations.

The most useful data to obtain in the near future would be near-simultaneous UB $V$  or  $uvby$  photometry and high resolution spectroscopy of a number of the unusual F stars – data obtained at multiple sites around the globe. Another very useful observing program would be to follow up the type of observations carried out by Antonello & Mantegazza (1986). Array photometry of open clusters, if obtained to the 0.01 mag level, should reveal new F dwarf variable stars

with “slow” periods such as the stars discussed here. This is a big undertaking, because these stars have periods on the order of one day, so either massive quantities of data must be obtained at a single site, or data must be obtained at multiple sites to derive the true periods of the variations.

F dwarf stars are only slightly more massive, slightly larger, and slightly hotter than the Sun. It is surprising that a number of them found outside the cool edge of the Cepheid instability strip in the HR Diagram have been found to be variable at the 0.10 mag level, whereas the Sun is constant to better than 0.001 mag (Hudson 1988). Our slowly varying F stars are definitely *not*  $\delta$  Scuti stars, and they remind us that new phenomena can still be discovered in otherwise normal stars.

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